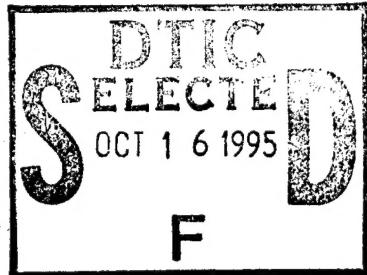


GRADUATE AERONAUTICAL LABORATORIES  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
Pasadena, California 91125

FINAL TECHNICAL REPORT



to

Office of Naval Research

Grant N00014-92-J-1072

entitled

Parallel Computation of Three-Dimensional,  
Unsteady Wake Flows Using Vortex Methods

1 October 1991 to 31 March 1994

DISTRIBUTION STATEMENT A

Approved for public release  
Distribution Unlimited

Principal Investigator Anthony Leonard  
Anthony Leonard

Professor of Aeronautics

Graduate Aeronautical Laboratories  
Division of Engineering & Applied Science  
California Institute of Technology  
Pasadena, California 91125

21 February 1995

1 March 1995

19951012 019

## Parallel Computation of Three-Dimensional, Unsteady Wake Flows Using Vortex Methods

### Technical Objectives

The objectives of the research were to develop computational techniques for parallel computers capable of simulating complex, three-dimensional, unsteady wake flows at high Reynolds numbers and to apply these techniques to such flows as those about maneuvering three-dimensional bodies. A Lagrangian vortex method was used as a basis for the numerical scheme. In vortex methods the only grid required is that to mesh the surface of the body. In addition, the computational elements containing vorticity move with the local fluid velocity and are required only in the boundary layers and wake of a bluff body flow. This technique is therefore a natural candidate for the simulation of wake flows in that the fluid containing vorticity for these flows occupies only a small fraction of the total fluid volume of interest.

### Technical Approach

A robust vortex particle method for three-dimensional flows was developed, including a new treatment of viscous effects to allow for the accurate treatment of boundary layer mechanics including unsteady separation. In addition, to allow for ambitious, three-dimensional applications, fast algorithms were developed for both the vortex particle method and the panel method (used to satisfy the no-slip boundary condition on the body surface). These algorithms were implemented on the Intel Delta supercomputer at Caltech. This 576 node machine has 528 Intel i860 numerical processors giving a total computing capability of over 30 Gflops peak performance with 8 Gbytes of memory.

### Accomplishments

We carefully considered three possible choices for a fast algorithm with regard to their speed, accuracy and implementation on a parallel computer. The various required translation operators were developed along with the necessary advanced error estimation techniques.

By working in close collaboration with J. K. Salmon (Research Fellow, Caltech Physics Department) we modified several versions of fast parallel tree codes developed for large scale 3D gravitational N-body problems into codes for 3D fluid dynamical N-vortex particle problems. On the Intel Delta with 512 processors, inviscid and viscous computations involving  $N = 10^5$  to  $10^6$  3D vortex particles were carried out successfully. Timings and scaling analyses were completed, covering the range:  $P = 2^n$  processors ( $n = 0, 1, 2, \dots, 9$ ) and  $N = 10^3 - 10^6$  vortex particles. They show that the CPU time,  $T$ , scales as  $T \propto \frac{N^{1.2}}{P}$ , and that the parallel overhead (obtained by measuring the difference between the  $P = 512$  curve and the extrapolation of the  $P = 1$  curve for large  $N$ ) is in the neighborhood of 20%.

In addition, the fast parallel tree code for vortex particles was itself modified into a code for boundary element methods (BEM) (also called panel methods). In its present implementation, panels that are infinitely thin vortex sheets are used. In the context of the present application, the vorticity represented by these panels is that required to satisfy the no-slip boundary condition at the body surface by creating the proper amount of boundary vorticity (i.e., "bound" vorticity) at every time step. This fast parallel tree code for M-panel problems has been used to compute potential flows past simple geometries such as the sphere and the ellipsoid at angle of attack. Timings were been carried out, spanning again the ranges  $P = 2^n$  processors ( $n = 0, 1, \dots, 9$ ) and  $M = 10^3 - 10^6$  vortex sheet panels, with the same type of scaling as obtained for the vortex particle code.

1 March 1995



The Ph.D. thesis work of P. Koumoutsakos which was completed 3 September 1992 gave us an excellent understanding of the creation and unsteady transport and diffusion of vorticity near a solid boundary vis-a-vis 2D, viscous vortex methods.

### Significance of Accomplishments

The development and implementation of the fast parallel tree code for 3D vortex particles on the Intel Delta constitutes a major building block of the present program, and, along with computations with  $N = 10^5 - 10^6$  3D vortex particles, represents a major accomplishment in the field of vortex dynamics. In a demonstration computation we studied the time-evolution of an initially spherical vortex sheet with  $N = 10^5$ . This proved very interesting and detailed: 3D instabilities, vortex structure interactions, etc.

The development and implementation of the fast parallel tree code for 3D boundary element methods on the Intel Delta also constitutes a major building block of the program, and a significant accomplishment. Whereas the state of the art in potential flow computations is usually in the range  $M = 10^3 - 10^4$  panels, we can now contemplate computing potential flows with  $M = 10^5 - 10^6$  panels. This fast panel code should be of great interest, not only in fluid mechanics: potential flow past bodies of very high complexity, free surface flows (e.g., marine engineering, wave dynamics, ship + wave dynamics), bubble flows (e.g., chemical engineering), etc.; but also possibly in other disciplines: electrostatics, radar, antennas, magnetostatics, acoustics, in fact most boundary integral problems expressed in terms of a Fredholm integral equation of the second kind and solved using a boundary element (= panel) method.

### Publications

#### Refereed Journals

1. G. S. Winckelmans and A. Leonard, "Contributions to vortex particle methods for the computation of three-dimensional incompressible unsteady flows", *J. Comput. Phys.*, **109**, 257, 1993.
2. J. K. Salmon, M. S. Warren and G. S. Winckelmans, "Fast parallel tree codes for gravitational and fluid dynamical N body problems", *International Journal of Supercomputer Applications*, **8**, 129-142, 1994.
3. G. S. Winckelmans, "Comments on a paper by Kiya et al. on the numerical simulation of pseudo-elliptical vortex rings using the vortex particle method", Brief communication in *Fluid Dyn. Res.*, **12**, 57-60, 1993 .
4. P. Koumoutsakos, A. Leonard and F. Pepin, "Boundary conditions for viscous vortex methods", *J. Comput. Phys.* **113**, 52, 1994.
5. P. Koumoutsakos and A. Leonard, "Improved boundary integral method for inviscid boundary condition applications", *AIAA Journal*, **31**, 401, 1993.
6. P. Koumoutsakos and A. Leonard, "High resolution simulations of the flow around an impulsively started cylinder using vortex methods", *J. Fluid Mech.* (to appear), 1995.
7. A. Leonard and P. Koumoutsakos, "High resolution vortex simulation of bluff body flow", *J. Wind Eng. and Indust. Aero*, **46** and **47**, 1993, 31-325.

*Conference Proceedings*

1. G. S. Winckelmans, A. Leonard and J. K. Salmon, "Computing unsteady 3D incompressible flows at high Reynolds number using a fast implementation of the vortex particle method", Proceedings of the Second CSCC (Concurrent Supercomputing Consortium) Delta Application Workshop, Norfolk, VA, 25-26 March 1993.
2. G. S. Winckelmans, J. K. Salmon, M. S. Warren and A. Leonard "The fast solution of three-dimensional fluid dynamical N-body problems using parallel tree codes: Vortex element method and boundary element method", Seventh SIAM Conf. on Parallel Processing for Scientific Comp., Feb. 1995, San Francisco.
3. P. Koumoutsakos and A. Leonard, "Numerical simulations of the flow passed a circular cylinder performing rotary oscillations", AIAA Paper No. 93-3276, Shear Flow Conf., Orlando, FL, 1993.
4. G. S. Winckelmans, J. K. Salmon, M. S. Warren and A. Leonard, "The fast solution of three-dimensional fluid dynamical N-body problems using parallel tree codes: Vortex element method and boundary element method," Seventh SIAM Conf. on Parallel Processing for Scientific Comp., Feb. 1995, San Francisco.

*Books (and sections thereof) Published and Theses*

1. P. Koumoutsakos and A. Leonard, "Direct simulations using vortex methods, in: *Vortex Flows and Related Numerical Methods.*, J. T. Beale, G.-H. Cottet and S. Huberson (eds.) NATO ASI Series C: 395, Kluwer Academic Publishers.
2. P. Koumoutsakos, "Direct numerical simulations of unsteady separated flows using vortex methods, 1992, Ph.D. thesis, California Institute of Technology, Pasadena.

*Presentations*

1. Presentations at the Naval Undersea Warfare Center, Newport, RI; University of California at San Diego, Rice University, Beijing University of Aeronautics and Astronautics, China Aeronautics Research and Development Center, Beijing Institute for Aerodynamics, Northwestern Polytechnical University of Xian, PRC.
2. A. Leonard was invited for the Midwest Mechanics Lecture Series, February/March 1992 (The University of Michigan, Michigan State University, University of Minnesota, University of Notre Dame, Illinois Institute of Technology, University of Illinois at Urbana/Champaign, Purdue University and University of Wisconsin at Madison). Dr. Leonard also gave an invited address to the First International Symposium on Computational Wind Engineering, Tokyo, August 21-24, 1992.
3. P. Koumoutsakos and A. Leonard, "Direct numerical simulations using vortex methods", in vortex flows and related numerical methods, in "Vortex flows and related numerical methods", NATO ASI Series, Grenoble France, 1992.

*Awards*

A. Leonard was elected Fellow of the American Physical Society.

*Personnel*

- Anthony Leonard, professor of aeronautics, is the PI. Petros Koumoutsakos, a postdoctoral fellow supported partially by the NSF, worked full time on the project. Gregoire Winckelmans also worked full time as a postdoctoral fellow until August 1993. Douglas Shiels, a Caltech senior, worked on the project part time during the academic year 1992-93 and as a graduate research assistant. Ryan Mackay, a graduate research assistant, spent the summer of 1993 on generating computer graphics displays.